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IN
2024-T351 ALUMINUM

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ABSTRACT

The sensitization of 2024-T351 to stress-corrosion cracking after exposure at 250°F has been measured using precracked double cantilever beam (DCB) specimens taken in the short-transverse grain direction from 1-in.-thick plate. The susceptibility of the material was assessed by measuring stress-corrosion crack growth rates as a function of the plane-strain stress intensity K_I in specimens periodically wetted with a 3.5% NaCl solution. The results show that at K_I levels of 8 and 10 ksi $\sqrt{in.}$, growth rates began to increase within the first 2 hr of exposure and continued to increase until approximately 50 hr of exposure. At K_I levels of 15 and 20 ksi $\sqrt{in.}$, increases in crack growth rates were not apparent until after 2 hr of exposure, but increased to a maximum in only 15 hr. The maximum difference in crack growth rate between unexposed and exposed specimens was greater than 100% at K_I levels of 8 and 10 ksi $\sqrt{in.}$ but only about 60% at the higher K_I levels.

INTRODUCTION

The aluminum alloy 2024-T3 is currently used in several aircraft applications where exposure to elevated temperatures is encountered. Such exposure may result from the service environment or the curing of certain adhesively bonded assemblies during fabrication. The effects of curing treatments on the mechanical properties and corrosion and stress-corrosion resistance of 2024-T3 are of interest because such factors bear heavily upon the integrity of fabricated parts.

Early work by Robertson (1) showed the effects of exposure temperatures from 266°F to 400°F on the mechanical and corrosion properties of 0.057-in.-thick 2024-T3 sheet. Some of Robertson's data is shown in

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Figs. 1 and 2 where it may be noted that the higher the exposure temperature, the less the exposure time required for the onset of sensitization to corrosion attack: at 266°F, 5 hr are required, while at 374°F only 0.8 hr is required. The data also indicate that continued exposure at either 266°F or 374°F eventually results in corrosion properties which approach those of unsensitized material.

Susceptibility to stress-corrosion cracking of 2000 series alloys (such as 2024-T3) after exposure to elevated temperatures has been related to the precipitation of $CuAl_2$ at grain boundaries (2). During the initial stages of aging, $CuAl_2$ precipitation occurs more rapidly at grain boundaries than within grains, which lowers the copper content in regions adjacent to the boundaries. Since copper in solid solution changes the electrode potential in the cathodic direction, lowering the copper content in regions adjacent to the boundaries makes these regions anodic to the grain interiors. In an appropriate electrolyte such as a sodium chloride solution, the copper-depleted regions corrode preferentially by an electrochemical process (2). The maximum difference in potential between grain boundaries and grain centers occurs at an intermediate aging time. At longer aging times, continued formation of precipitates within the grains begins to equilibrate the potentials in the two regions. After prolonged aging, the difference in electrode potential is reduced to almost zero, as shown in Figs. 3 and 4. Note in these figures that the minimum loss in tensile strength of stretched (5%) and aged 2024-T3, after exposure to a corrosive environment, occurred at the same aging time required to minimize the potential differences between grains and grain boundaries of the Al-4%Cu alloy: 16 hr at 375°F. From these data, one would anticipate the excellent stress-corrosion resistance of 2024 in the T851 temper, since this heat treatment is achieved by aging 2024-T351 for 12 to 16 hr at 375°F.

The current study was conducted to investigate the stress-corrosion performance of 2024-T351 after exposure to a temperature of 250°F for times up to 300 hr. This temperature is commonly used during the curing of adhesively bonded assemblies and is also very near the stagnation temperature of skin of aircraft operating at Mach 2. The approach used was to measure the effect of exposure time on stress-corrosion crack growth rates rather than determine strength losses in tension specimens.

MATERIALS AND TEST PROCEDURES

Double cantilever beam (DCB) specimens of the configuration shown in Fig. 5 were used in the current study. The advantages and use of this specimen in studying stress-corrosion cracking in high-strength aluminum alloys have been described by one of the authors (3,4,5,6,7, 8,9). Equation 1 (5) allows stress-corrosion crack growth rate data to be correlated with the plane-strain stress-intensity factor K_I :

$$K_I = \frac{vEh \left[3h\,(a + 0.6h)^2 + h^3\right]^{1/2}}{4\,\left[(a + 0.6h)^3 + h^2a\right]} \qquad (1)$$

where: v = total deflection of the two arms of the DCB specimen at the load point (centerline of loading bolt)

E = modulus of elasticity (10.3×10^6 for aluminum alloys)

h = ½ specimen height

a = crack length measured from load point (centerline of loading bolt)

Obtaining the crack growth rate data involves the following test procedure. The loading bolt is turned until a sharp crack pops in from the end of the machined notch. Plane-strain fracture toughness K_{Ic} can be calculated at this point by measuring v and a following the pop-in and substituting these values in Eq. (1). For the lower strength 2024-T351 alloy evaluated in this study, some plastic bending occurs in the arms of the DCB specimens on loading to pop-in. This contribution to deflection v must be subtracted from the total v before calculating K_{Ic} and subsequent K_I levels. After the crack has been advanced a few tenths of an inch by several pop-ins, the bolt is left fixed, v and a are measured, and the 3.5% NaCl environment is applied. Under these conditions the load P and stress-intensity factor K_I at the crack tip decrease as the stress-corrosion crack length increases with time (Figs. 6b and 6c). The slope of the resulting crack length-time curve in Fig. 6a then provides the crack growth rate as a function of K_I. As the crack length a increases and K_I decreases, a K_I level may eventually be reached below which growth ceases or is negligible. This K_I level, designated K_{Iscc}, is shown in Fig. 6c. The use of DCB specimens is especially suited to aluminum alloys with elongated grain structures, since stress-corrosion cracking is intergranular and cracks are kept in plane by the elongated grain structure of the material.

For this study, 14 DCB specimens were machined from 1-in.-thick 2024-T351 plate. Duplicate specimens were aged in a 250°F ± 3°F oil bath for 2, 5, 15, 50, 100, and 300 hr. Two additional baseline specimens were tested in the unexposed (T351) condition.

All specimens were loaded to K_{Ic} and the steel bolts insulated by masking the entire bolt end of the specimens with a vinyl coating. The specimens were then placed upright (bolt end up) and, with a polyethylene squeeze bottle, several drops of a 3.5% NaCl solution were placed in the crack three times each working day at 4-hr intervals. Crack lengths were monitored to the nearest 0.01 in. using a 30-power wide field microscope and a scale. Crack length-time data were taken over a three-week period, at which time all specimens were broken open and inspected.

RESULTS AND DISCUSSION

The effect of exposure time at 250°F on stress-corrosion crack growth rates in 2024-T351 is shown in Fig. 7. It can be seen that there is excellent agreement between the duplicate DCB specimens. The stress-corrosion crack growth rates are observed to increase generally with time at temperature, an effect illustrated more clearly by plotting stress-corrosion crack growth rates for various K_I levels as a function of exposure time at 250°F, as shown in Fig. 8. Several trends can be noted. At the lower K_I levels (8 and 10 ksi $\sqrt{\text{in.}}$), stress-corrosion crack growth rates started to increase almost immediately upon exposure at 250°F. Maximum susceptibility appeared to be reached after about 50 hr of exposure; thereafter growth rates remained nearly constant. At K_I levels of 15 and 20 ksi $\sqrt{\text{in.}}$, increases in crack growth rates were not apparent until after 2 hr of exposure. Maximum susceptibility was reached after 15 hr of exposure at which time crack growth rates stabilized at about a 60% increase over initial values. The trends observed in Fig. 8 are also apparent when the total crack growth at one week was plotted against exposure time at 250°F, as illustrated in Fig. 9.

Taken together, the stress-corrosion crack growth rate data obtained during the present investigation show susceptibility trends that are similar to those obtained in the mechanical-property degradation tests reported earlier (1). The primary difference is that data for exposure at 250°F obtained using the precracked DCB specimen technique show some increases in susceptibility at low K_I levels almost immediately after exposure, while the published data for exposure at 266°F show no increase in susceptibility until after 5 hr. The similarity in results is somewhat surprising since Robertson (1) used 0.057-in.-thick sheet, whereas the current study used 1-in.-thick plate. This thickness variation results in large differences in cooling rate during quenching from the solution treatment temperature, and cooling rate has been shown by Willey (10) and Lifka and Sprowls (11) to have a strong influence on intergranular and stress-corrosion cracking susceptibility of 2024-T3. The cooling rate of 0.057-in.-thick sheet quenched into 72°F water is about 5000°F/sec, while that of 1.0-in.-thick plate is about 90°F/sec (11). The effect of such a difference in quench rate on corrosion and stress-corrosion properties is shown in Fig. 10 (11), where it can be seen that the 0.057-in.-thick sheet should be near maximum immunity and the 1.0-in.-thick plate should be near maximum susceptibility. The effects of quench rate on corrosion and stress-corrosion susceptibility are considered to be due to localized electrochemical differences caused by the formation of grain-boundary precipitates and solute-depleted zones during the quench (2,12), an explanation that is similar to that for sensitization to corrosion and stress corrosion after exposure at elevated temperatures.

In conclusion, the data indicate that sensitization of 2024-T3 to intergranular and stress-corrosion attack can occur within very short exposure times at 250°F. Crack growth rates before and after exposure were noted to change more than 100% for K_I levels of 8 and 10 ksi $\sqrt{in.}$

and about 60% for K_I levels of 15 and 20 ksi $\sqrt{in.}$ The speed and degree of sensitization suggest that fabrication and service temperatures must be carefully selected with respect to stress-corrosion requirements.

ACKNOWLEDGMENTS

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REFERENCES

1. W. D. Robertson, "Correlation of Mechanical Properties and Corrosion Resistance of 24S-type Aluminum Alloys as Affected by High-Temperature Precipitation," Transactions of the American Institute of Mining and Metallurgical Engineers, Institute of Metals Division, Vol. 166, 1946, p. 216.

2. R. B. Mears, R. H. Brown, and E. H. Dix, Jr., "A Generalized Theory of the Stress Corrosion of Alloys," Symposium on Stress-Corrosion Cracking of Alloys, ASTM-AIME, 1945.

3. J. C. McMillan and M. V. Hyatt, Development of High-Strength Aluminum Alloys With Improved Stress-Corrosion Resistance, Technical Report AFML-TR-148, June 1968.

4. NRL Memorandum Report 1941, Seventh Quarterly Report, ARPA Coupling Program on Stress-Corrosion Cracking, October 1968.

5. M. V. Hyatt, Use of Precracked Specimens in Stress-Corrosion Testing of High-Strength Aluminum Alloys, D6-24466, The Boeing Company, November 1969.

6. M. V. Hyatt, Use of Precracked Specimens in Selecting Heat Treatments for Stress-Corrosion Resistance in High-Strength Aluminum Alloys, D6-24467, The Boeing Company, November 1969.

7. M. V. Hyatt, Effects of Residual Stresses on Stress-Corrosion Crack Growth Rates in Aluminum Alloys, D6-24469, The Boeing Company, November 1969.

8. M. V. Hyatt, Effects of Specimen Geometry and Grain Structure on Stress-Corrosion Cracking Behavior of Aluminum Alloys, D6-24470, The Boeing Company, November 1969.

9. M. V. Hyatt, Effect of Quenching Rate on Stress-Corrosion Crack Growth Rates in 2024-T4 Aluminum, D6-24471, The Boeing Company, November 1969.

10. E. H. Dix, Jr., "Thermal Treatment of Aluminum Alloys," Physical Metallurgy of Aluminum Alloys, American Society for Metals, 1949, pp. 200-240.

11. H. Y. Hunsicker, "The Metallurgy of Heat Treatment," Aluminum, Vol. I: Properties, Physical Metallurgy, and Phase Diagrams, edited by K. R. Van Horn, American Society for Metals, 1967, pp. 109-162.

12. M. S. Hunter, G. R. Frank, Jr., and D. L. Robinson, "Mechanism of Corrosion of 2024 Alloy as Revealed by Electron Microscopy," Proceedings of Second International Congress on Metallic Corrosion, National Association of Corrosion Engineers, 1963.

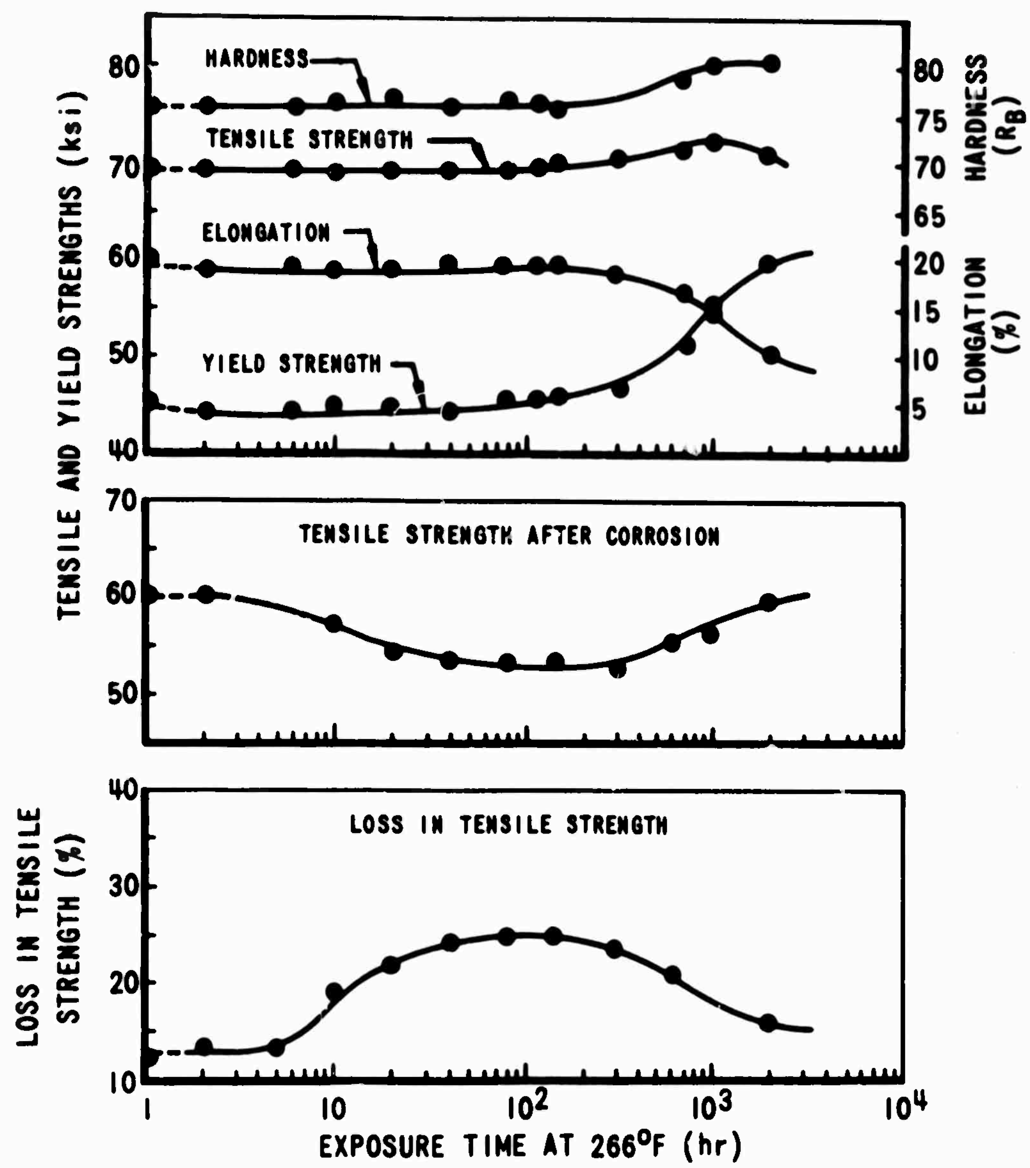

Figure 1 Effect of exposure time at 266°F on mechanical properties and corrosion characteristics of longitudinal 2024-T3 sheet specimens (data from Ref. 1). Corrosion specimens were stressed to 80% of their tensile yield strength and periodically immersed for 48 hr in a 5% NaCl solution containing 0.3% H_2O_2.

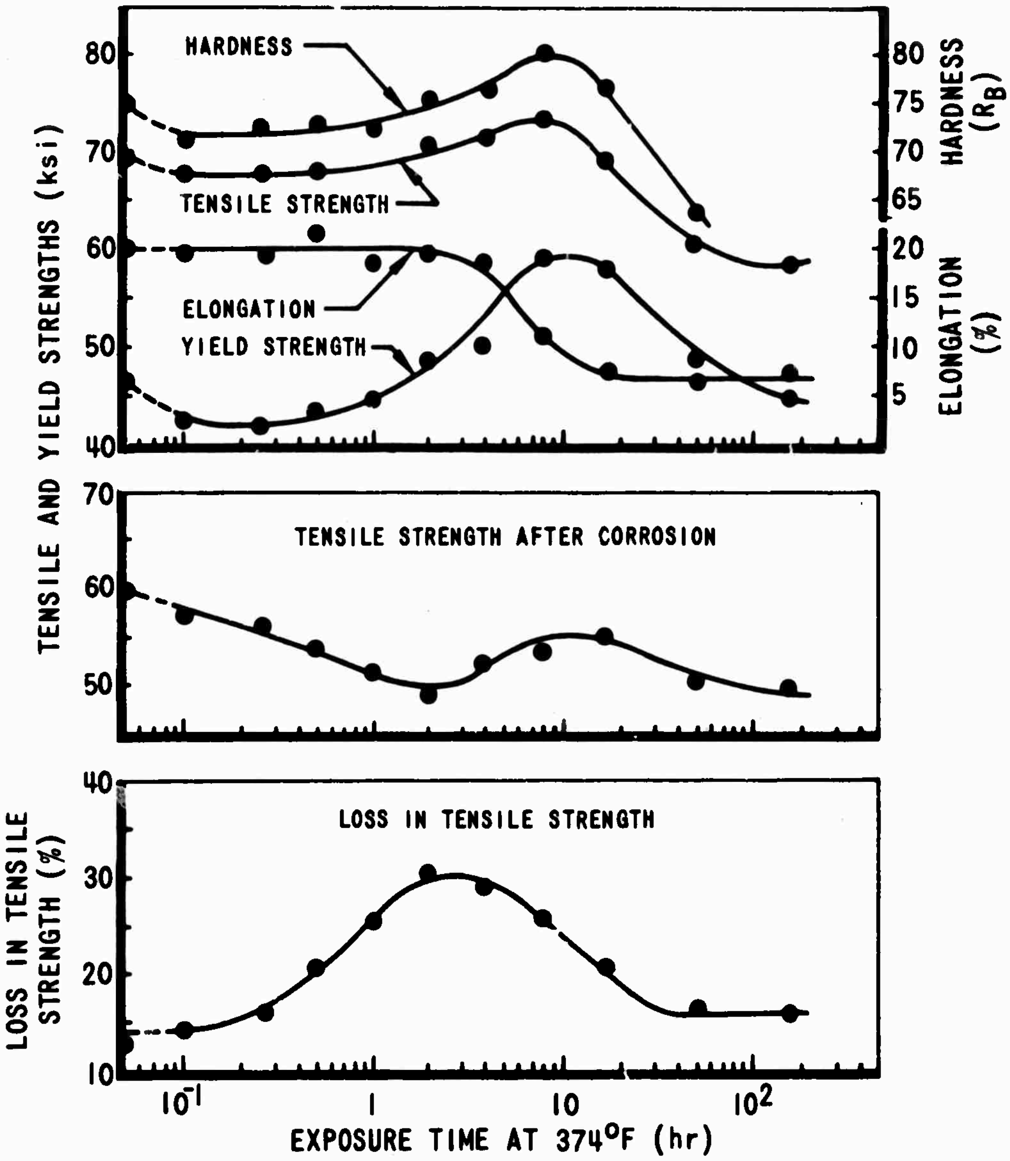

Figure 2 Effect of exposure time at 374°F on mechanical properties and corrosion characteristics of longitudinal 2024-T3 sheet specimens (data from Ref. 1). Corrosion specimens were stressed to 80% of their tensile yield strength and periodically immersed for 48 hr in a 5% NaCl solution containing 0.3% H_2O_2.

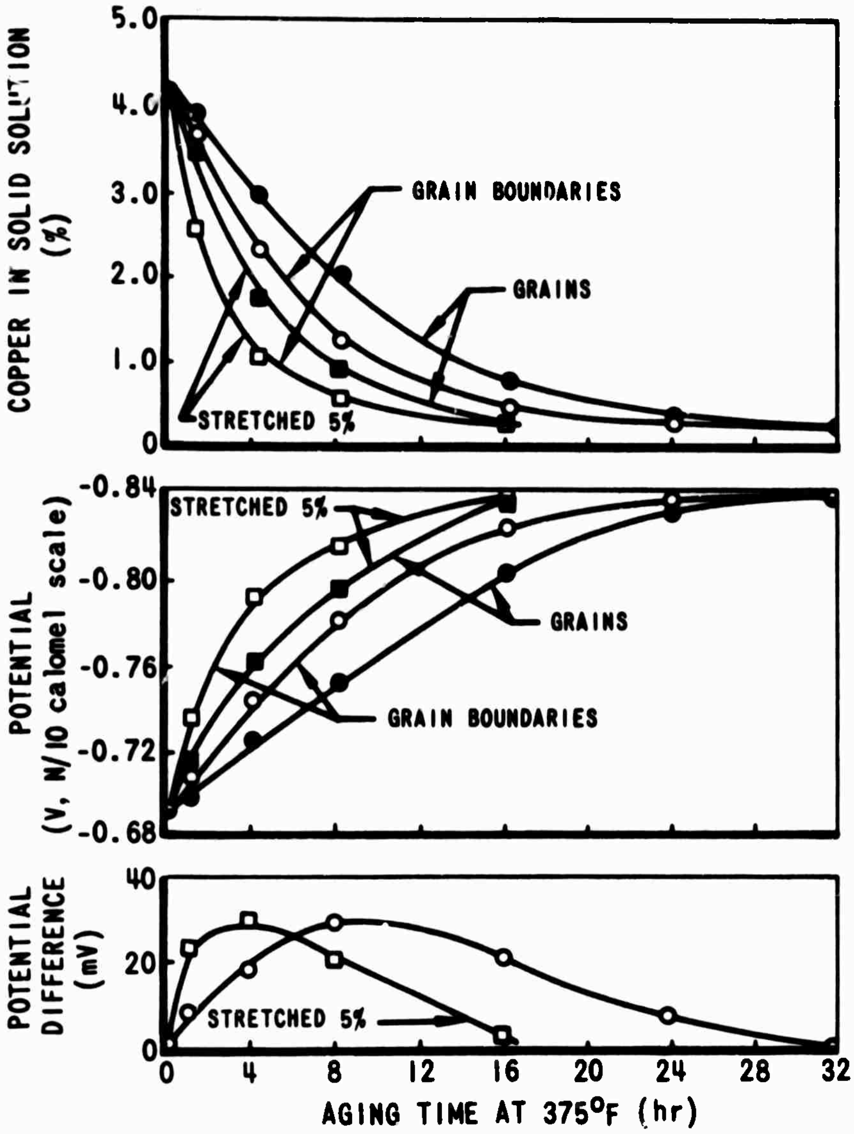

Figure 3 Potentials of the grains and grain boundaries of an Al-4%Cu alloy heat treated at 930°F, quenched in cold water, and aged at 375°F (data from Ref. 2).

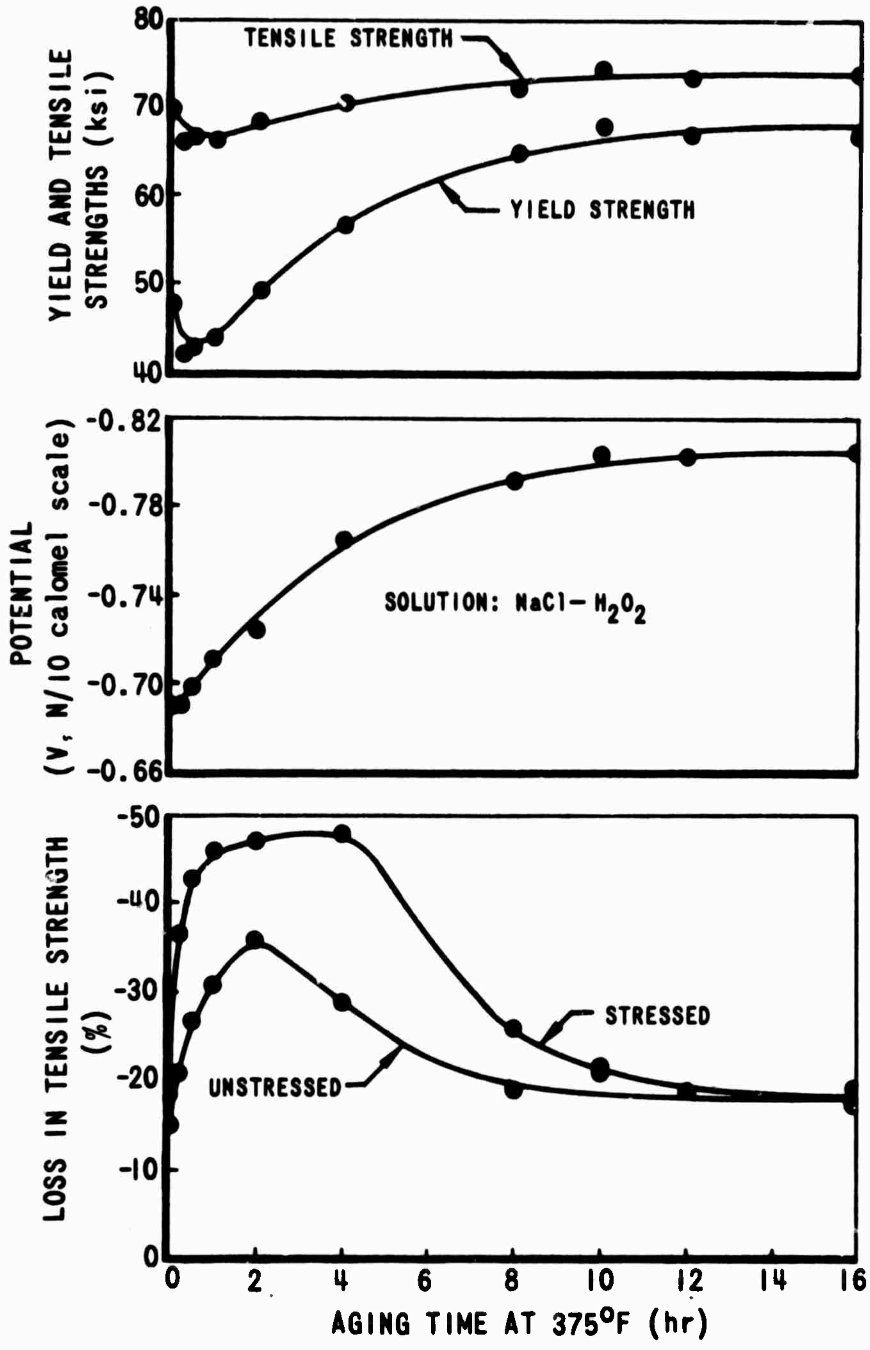

Figure 4 Effect of aging time at 375°F on tensile strength, yield strength, solution potential, and resistance to corrosion and stress corrosion of the commercial Al-Cu-Mg-Mn alloy 2024-T3 (stretched 1.5% after quenching). Corrosion and stress-corrosion resistance were evaluated after 48 hr of exposure to NaCl-H_2O_2 solution by alternate immersion (1.5/1.5 min cycle) (data from Ref. 2).

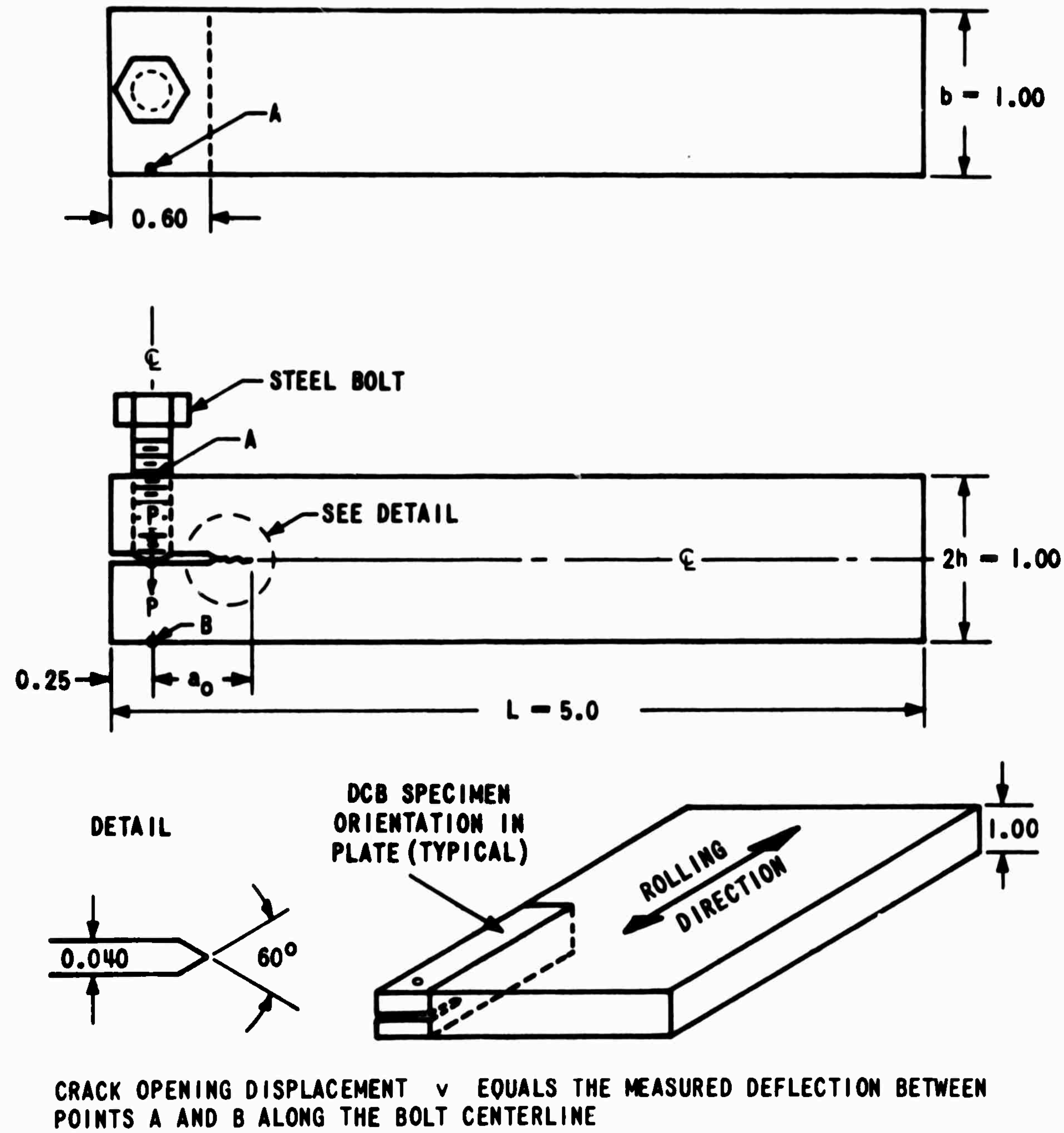

Figure 5 Double cantilever beam specimen used for stress-corrosion testing of high-strength aluminum alloys (from Ref. 5).

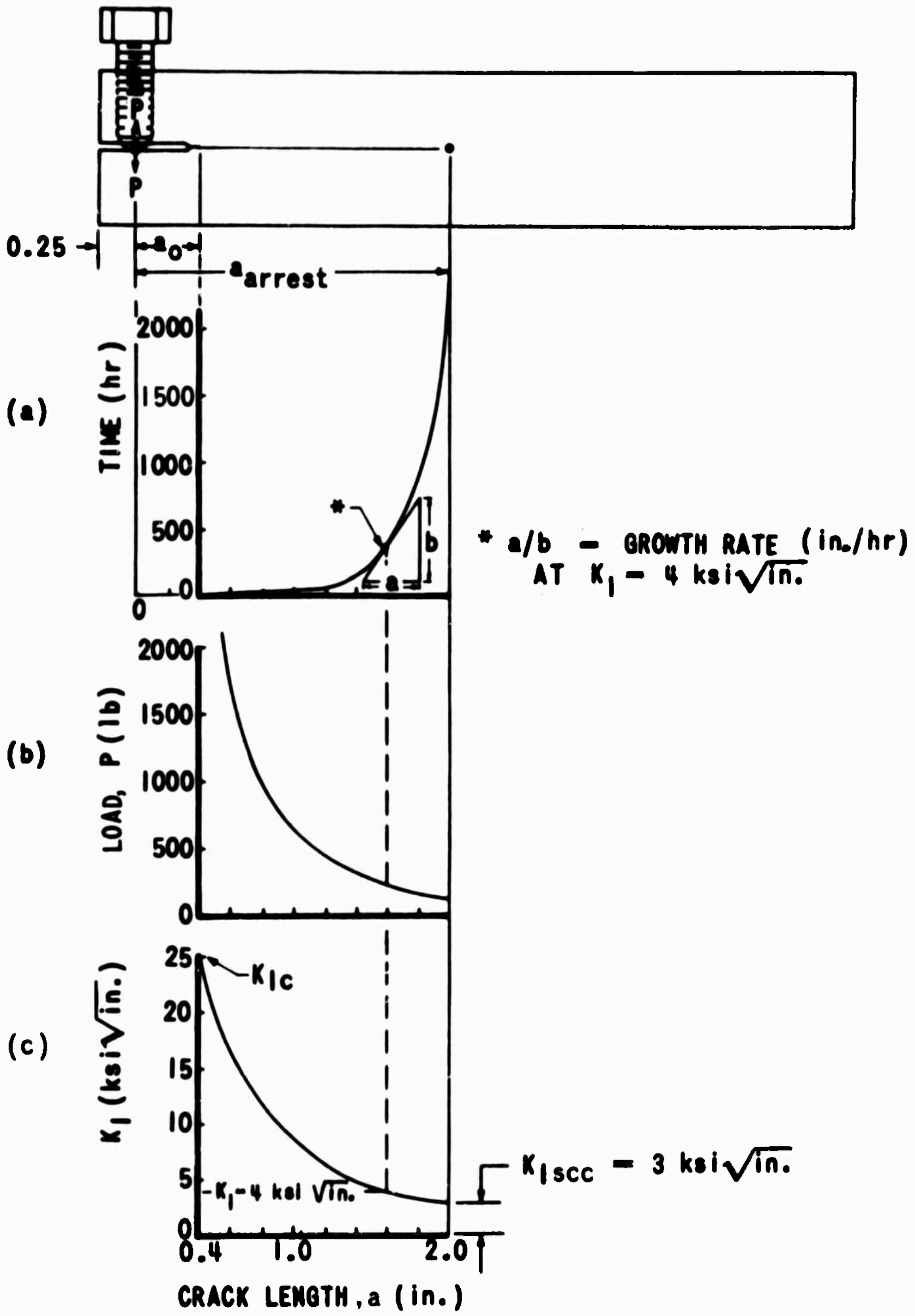

Figure 6 Effect of crack growth on load and stress intensity under constant crack opening displacement conditions (v = 0.010 in.) in a 1- by 1- by 5-in. aluminum alloy DCB specimen (from Ref. 5).

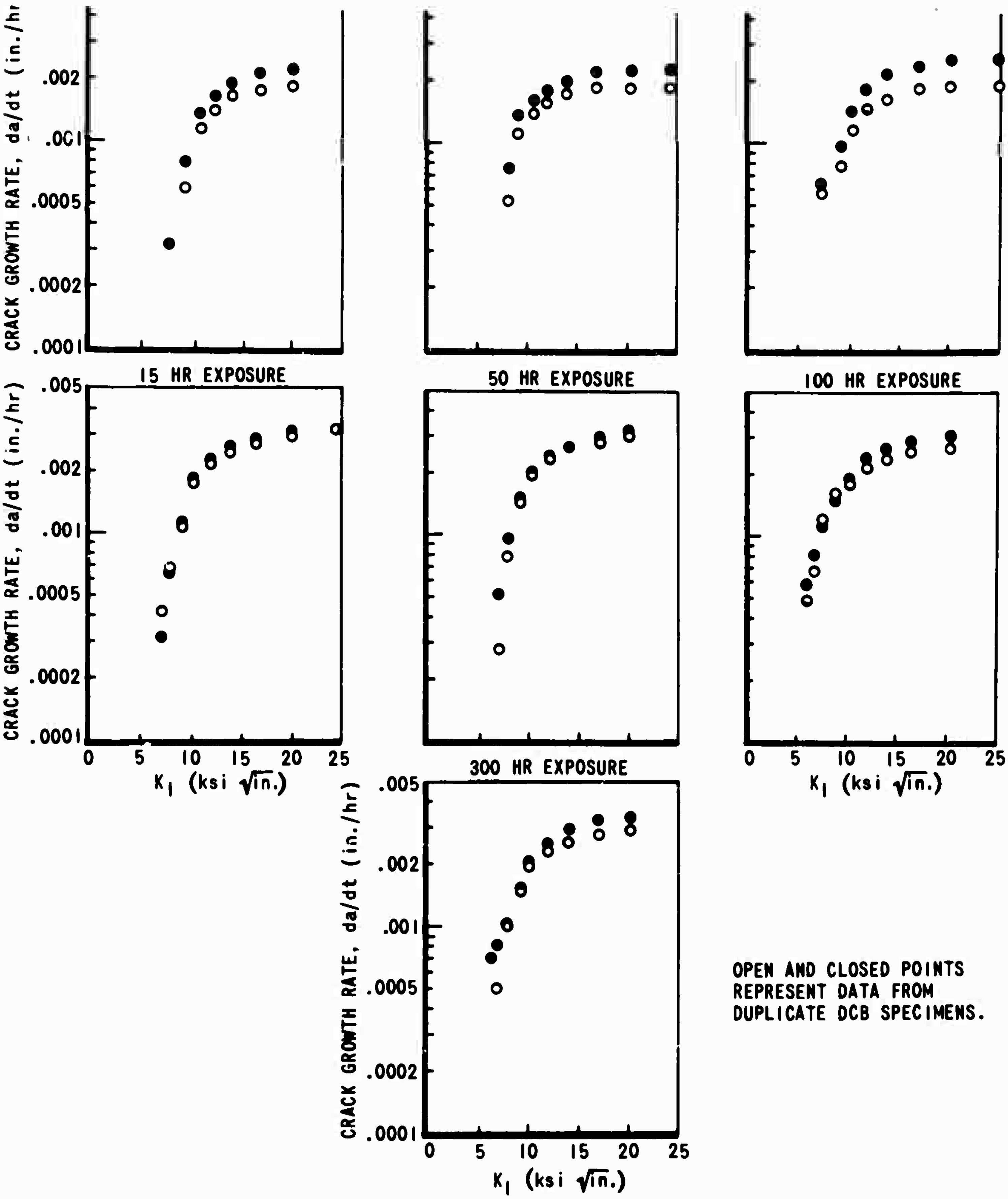

Figure 7 Effect of exposure time at 250°F on stress-corrosion crack growth rates in DCB specimens from 2024-T351 plate.

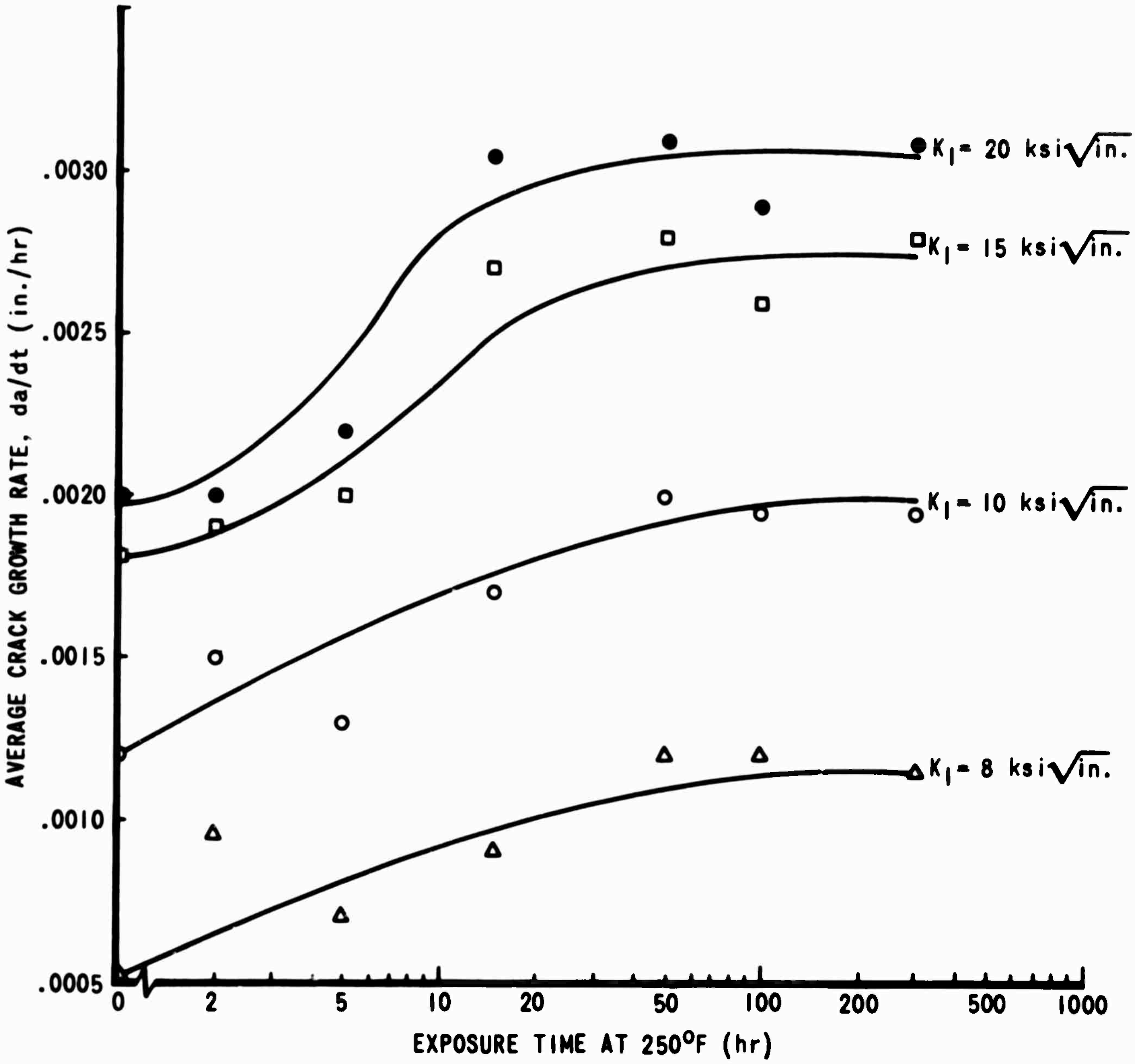

Figure 8 Effect of exposure time at 250°F on stress-corrosion crack growth rate at various K_I levels in DCB specimens from 2024-T351 plate.

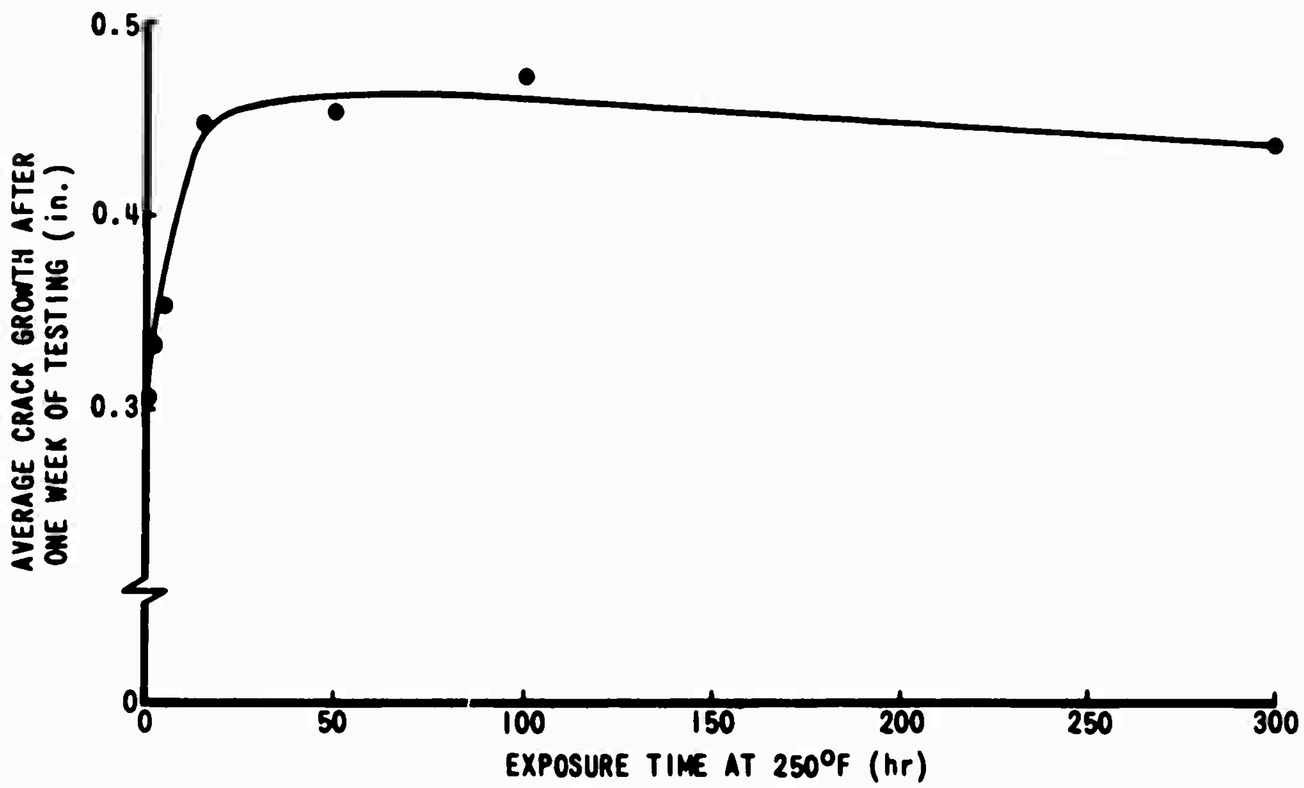

Figure 9 Effect of exposure time at 250°F on stress-corrosion crack growth in 2024-T351 DCB specimens after one week of testing.

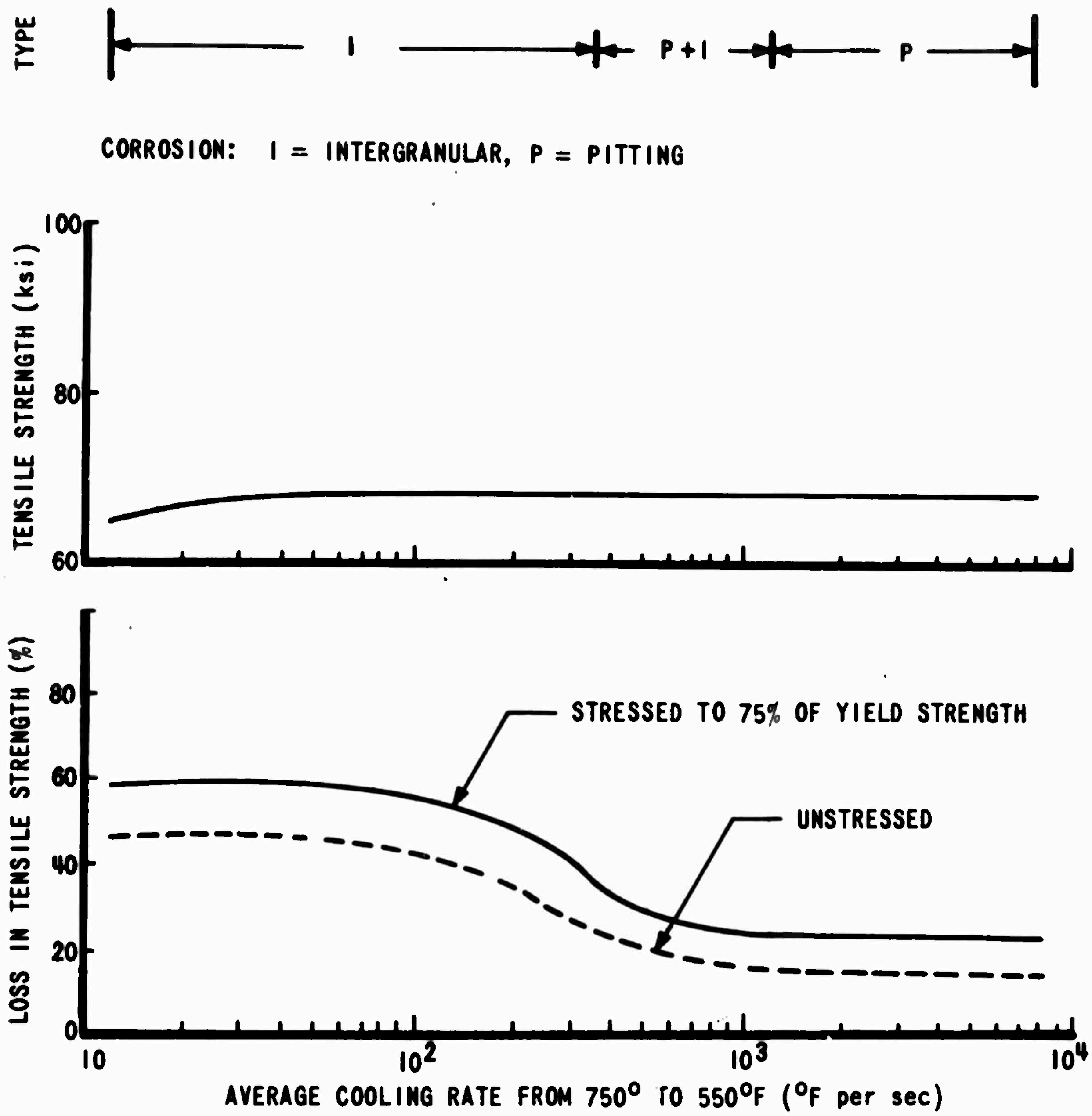

Figure 10 Effect of quenching rate on tensile properties and corrosion resistance of 2024-T4 sheet. Stressed and unstressed specimens were exposed to alternate immersion in 3.5% NaCl solution for 12 weeks before testing (from Ref. 11).

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13. ABSTRACT

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	ROLE	WT	ROLE	WT	ROLE	WT
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Crack Growth Rate						
Stress Intensity Factor						
Double Cantilever Beam Specimen						
Elevated Temperature Exposure						